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A Quantum Gas of Cold Li Atoms

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12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Work by Prof. Ketterle and his collaborators is summarized here.

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14. SUBJECT TERMS

15. NUMBER OF PAGES

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17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

A quantum gas of cold lithium atoms

Final Technical Report

At the end of each grant period (generally three years) a final technical report is required. This report must be mailed to a list supplied to you at the beginning of the grant period. It is due no later than 90 days after the end of your grant. You can include it in a renewal proposal, if you are submitting one, to provide the background/progress part of your proposal. The format of this report has been changed, however! An outline of the required format follows:

1. Title of Grant: A quantum gas of cold lithium atoms

2. Principal Investigator: David E. Pritchard, Wolfgang Ketterle

3. R&T Code AASERT, N00014-94-1-0807

4. Funding profile:

Indicate the total grant amount and the amount of each yearly increment. If equipment was purchased, indicate the amount spent and a brief description of the equipment.

Year 1: 55 k, Year 2: 57 k; Year 3: 59 k; Total 171 k
Equipment: none.

5. Technical objective:

In bullet format indicate what the goals were of your project. Be concise. More than one objective is OK, but do not exceed three.

The proposal contained the following goals:

- Realization of evaporative cooling of magnetically trapped atoms
- Development of new magnetic trap configurations
- Intense source of cold lithium atoms (this goal was dropped)

6. Published papers resulting from this support (numbers only):

a. Submitted but not published 1
b. Published in refereed journals 9
c. Published in non-refereed journals 1

7. Number of technical reports submitted 13 conference abstracts

8. Number of books written none

9. Number of book chapters written none

10. Patents as a result of this work

a. Number of applications filed none
b. Number of patents granted (include patent number and date of patent) none

11. Total number of presentations given about 80

List 1 - 3 of the most significant. Include forum, date, title, and a couple of sentences describing the significance of the presentation.

- W. Ketterle:
  Observation of Bose-Einstein condensation in a gas of sodium atoms.
  Workshop on ϶Collective effects in ultracold atomic gases™, Les Houches, France, April 1-5, 1996, Book of Abstracts, p. 53.

  In this talk, the MIT group presented the new cloverleaf magnetic trap, a superior trap for achieving Bose-Einstein condensation, and dispersive imaging, a method to observe Bose condensates in a non-destructive way.

- W. Ketterle, M.R. Andrews, D.S. Durfee, D.M. Kurn, M.-O. Mewes, C.G. Townsend, and N.J. van Druten:
  Bose-Einstein condensation of sodium atoms.
  XXIth International Conference on Low Temperature Physics (LT 21) Aug. 8-14, 1996, Prague, Czech Republic, Conference Handbook, p. 133.

  This was an invited talk at the major international meeting for low temperature physics and demonstrated that the study of ultracold gases has now become a new interdisciplinary field of atomic and condensed matter physics.

- K.B. Davis, M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle:
  Bose-Einstein condensation in a gas of sodium atoms.
  XX International Quantum Electronics Conference IQEC'96, Sydney, Australia, July 14-19, 1996, Technical Digest, p. 28.

  IQEC is the most important international meeting on quantum electronics. In an invited talk, W.K. presented first results on creating two condensates and the rf output coupler. A few months later, this work developed into the realization of an atom laser.

12. Honors and awards received during the granting period:
List individually and include: Source, title, recipient, and date. Underline those that at least in part resulted from your ONR funding.

- 1996 K.B. Davis, Finalist for the 1996 Award for Outstanding Doctoral Thesis Research in Atomic, Molecular, or Optical Physics, American Physical Society.
- 1996 David and Lucile Packard Fellowship (W.K.)
- 1997 I.I. Rabi Prize of the American Physical Society (W.K.)
- 1997 Gustav-Hertz Prize of the German Physical Society (W.K.)
- 7/1997 Promotion to Full Professor with tenure (W.K.)

All these prizes resulted at least in part from ONR funding.

13. Number of different post-docs supported at least 25% of the time for at least one calendar year: none.
Estimate total person-months of post-doc support under this grant: none.

14. Number of different graduate students supported at least 25% of the time for at least one calendar year: three.
Estimate total person-months of graduate student support under this grant: 48.

15. List 2 - 5 of the most significant publications resulting from this work:

Include titles and full citations, as well as a few sentences indicating the significance of the publication.

- K.B. Davis, M.-O. Mewes, M.A. Joffe, M.R. Andrews, and W. Ketterle:
  Evaporative Cooling of Sodium Atoms.
  Phys. Rev. Lett. **74**, 5202 (1995); Erratum: Phys. Rev. Lett. **75**, 2909 (1995).
  Our group was the first to combine laser cooling with evaporative cooling. Evaporative cooling turned out to be the key technique for producing nanokelvin atoms.

- K.B. Davis, M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle:
  Bose-Einstein condensation in a gas of sodium atoms.
  Phys. Rev. Lett. **75**, 3969-3973 (1995).
  In this paper we reported the observation of BEC in atomic sodium, a few months after the first realization of BEC in rubidium. Our work used a new atom trap, the optically plugged magnetic trap, and achieved extremely high densities of atoms (larger than 10^{14} cm^{-3}). This resulted in evaporative cooling times of only seven seconds.

- M.R. Andrews, C.G. Townsend, H.-J. Miesner, D.S. Durfee, D.M. Kurn, and W. Ketterle:
  Observation of interference between two Bose condensates.
  Science **275**, 637-641 (1997).
  This paper was the first direct demonstration of coherence of Bose condensates. It showed that Bose condensates could be released from the magnetic trap and still interfere. This production of coherent atom beams was the realization of a basic atom laser.

16. Major accomplishments:

Here is the meat of what you did! In bullet format indicate the most significant accomplishments for the granting period.

- Observation of Bose-Einstein condensation in a dilute atomic vapor.
- The optically plugged magnetic trap - a novel hybrid trap using magnetic fields and far-off-resonant laser light.
- Rf induced evaporation.
- Evaporative cooling of atoms precooled by laser cooling.
- Realization of an output coupler for Bose-Einstein condensed atoms. This work provided a simple solution to the problem how to build an output coupler for an atom laser.
- Observation of interference between two condensates. This was the first direct evidence for coherence of Bose condensates, and proved the existence of long-range correlations.
- Study of sound propagation in a Bose condensate. We developed a novel way of exciting and observing collective excitations of a Bose condensate. The observation of propagating density perturbations resulted in the first measurement of the speed of sound of a Bose condensate.

17. Transitions:

Indicate any results from this grant that has attracted industrial or developmental interest. Indicate the source and form of interest. Give as much detail as possible. Example: SRC provided $100K in funding to determine if the etching process identified in our lab could be utilized by them in a manufacturing environment.

One aspect of our work is the ultimate control over the motion of atoms, at the quantum level. Such precise preparation of atoms might lead to better frequency standards, improved precision experiments and atom lithography with higher resolution. Our techniques are being used in several laboratories around the world, including national labs.

18. Summary of the overall impact of your work in this period.

Give a general statement of the impact of your work in relation to the objectives of the program. Also indicate if this work identified or stimulated a new research area.

The observation of Bose-Einstein condensation has been one of the major goals in atomic physics in the last ten years. This goal has been achieved in 1995 when Bose condensation was observed at JILA and at MIT, and evidence for reaching the quantum degenerate regime was obtained at Rice.

- The study of Bose-condensed gases is rapidly developing into a new subfield interdisciplinary between atomic and condensed matter physics. Quantum degenerate dilute gases have properties which are different from the quantum liquids helium-3 and helium-4. The study of BEC will therefore lead to further insight into macroscopic quantum phenomena.
- A Bose condensate is the ultimate source of ultracold atoms. The kinetic energy of a (released) Bose condensate is on the order of tens of nanokelvin. Such ultracold atoms are ideal for precision experiments (determination of fundamental constants, tests of fundamental symmetries) because the slow motion eliminates most systematic effects. Furthermore, such samples of atoms have potential applications in the field of atom optics, such as the creation of microscopic structures by direct-write lithography or atom microscopy. A Bose condensate may also find applications in metrology, improving frequency standards and atom interferometry.
- Our realization of an atom laser is the first step towards the use of coherent atom beams in atom optics, e.g. in atom interferometry and atom lithography.

19. Four (4) key words/phrases describing your project.

- Degenerate quantum gases
- Bose-Einstein condensation
- Cooling and trapping of neutral atoms
- Atom laser

20. Provide three (3) viewgraphs highlighting the science and technology associated with the overall project.

1. Evidence for Bose-Einstein condensation

Two-dimensional probe absorption images ("Shadows of atoms") after 6 ms time of flight, show evidence for BEC. Plotted is the density integrated along the line of sight versus the other two spatial coordinates. These images display the velocity distribution of the cloud after switching off the trap.

The left figure is the velocity distribution of a cloud cooled to just above the transition point, the middle figure is taken just after the condensate appeared, and the right figure after further evaporative cooling has left an almost pure condensate.

This figure shows the difference between the isotropic thermal distribution and an elliptical core attributed to the expansion of a dense condensate.

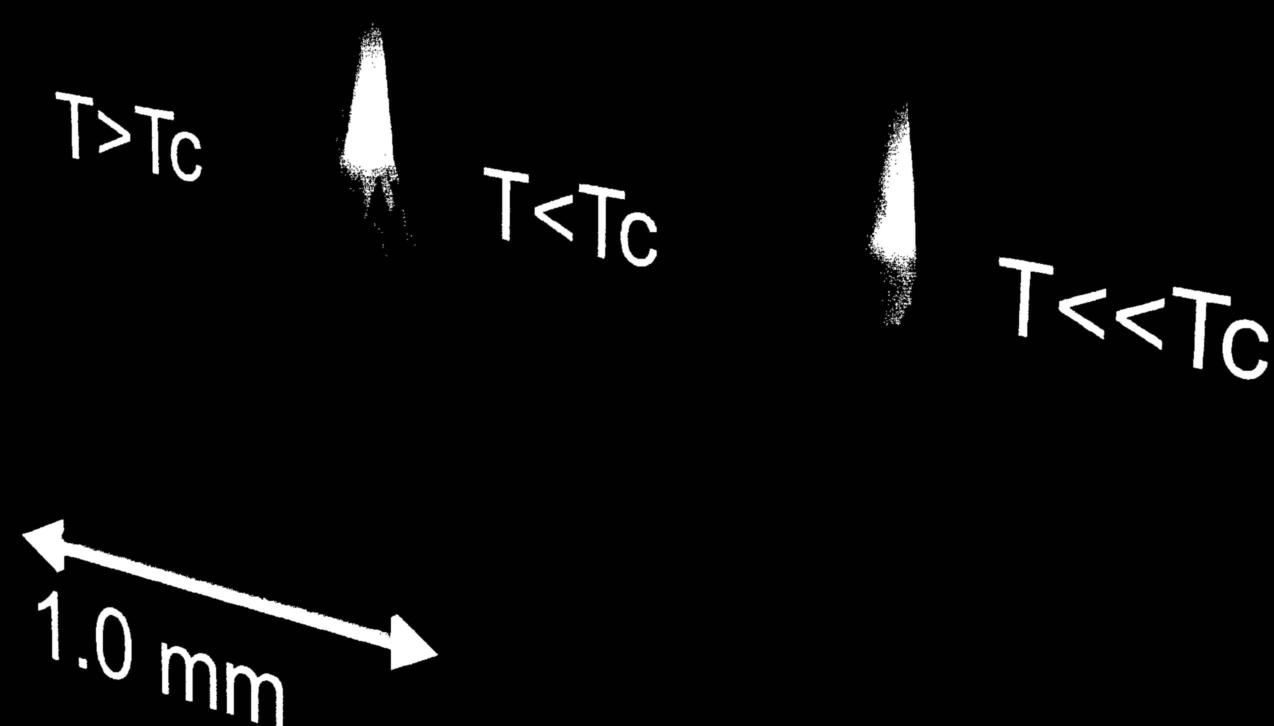
The width of the images is 0.9 mm. The total number of atoms around the phase transition is about 7x10^5 atoms, the temperature at the transition point is 2 microkelvin.

2. Demonstration of coherence of Bose-Einstein condensates: The spatial coherence of a Bose condensate was demonstrated by observing interference between two Bose condensates. They were created by evaporatively cooling sodium atoms in a double-well potential formed by magnetic and optical forces. High-contrast matter-wave interference fringes with a period of 15 micrometer were observed after switching off the potential and letting the condensates expand for 40 milliseconds and overlap

3. The MIT atom laser. Pulses of atoms were coupled out of a trapped Bose condensate by using an "rf output coupler". In this scheme, the magnetic moments of the atoms were rotated with an rf pulse, and then the Stern-Gerlach effect split the cloud into trapped (spin up) and non-trapped (spin down) components. Multiple output pulses could be created by using a sequence of rf pulses.

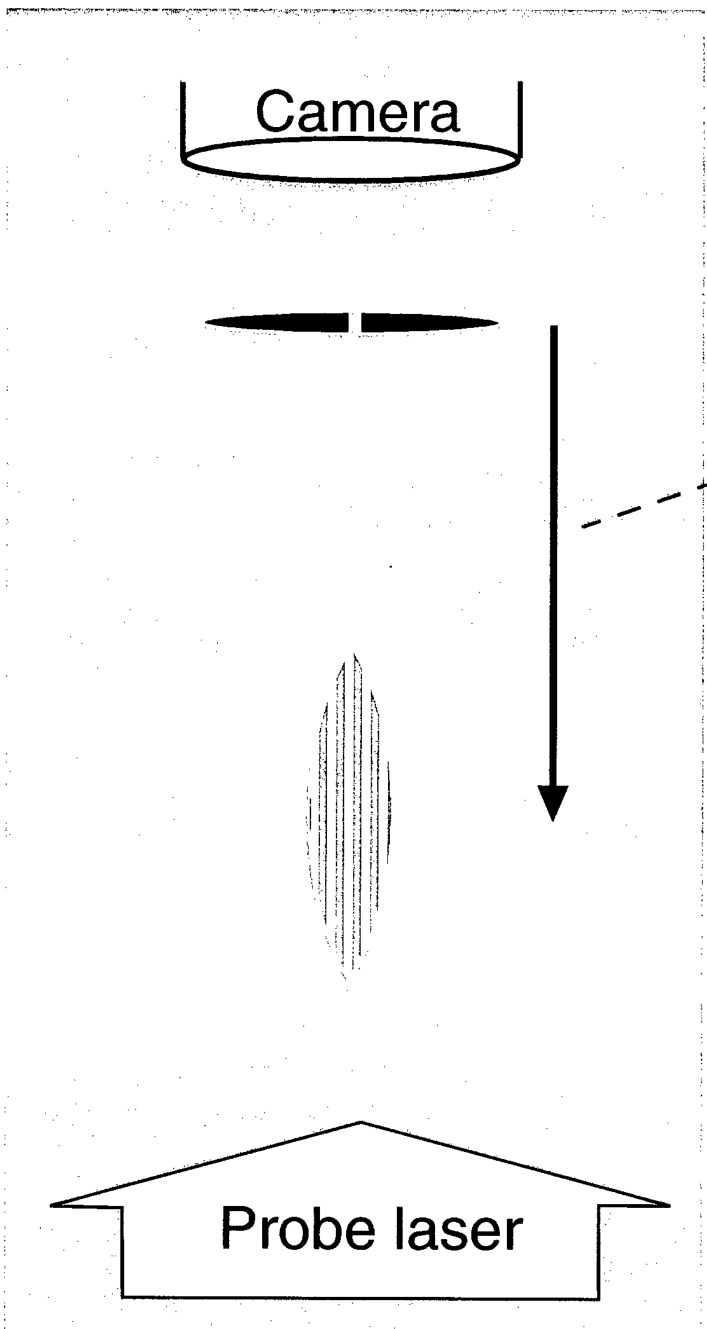
Interference between two outcoupled pulses (coupled out from a split condensate) proved that the rf output coupler preserved the coherence of the condensates. The controlled generation of intense coherent atomic beams was the first realization of a basic atom laser.

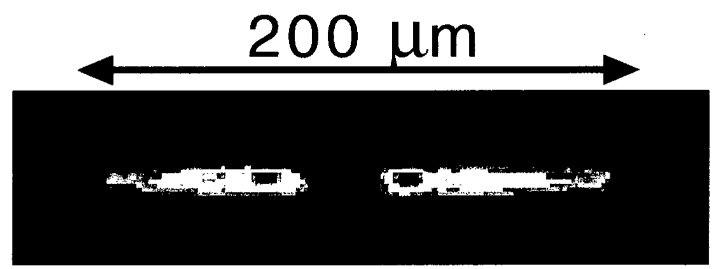
Expansion of a Bose-Einstein Condensate



MIT Sodium Trap
September/October 1995
rf evaporation + 6ms free expansion

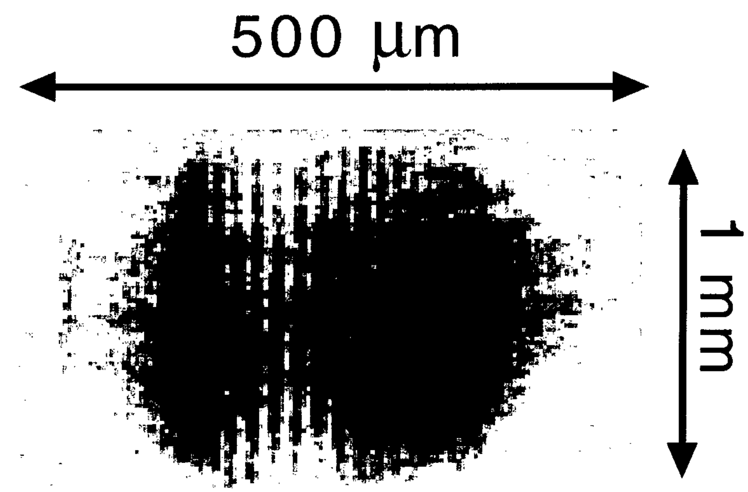
Interference of two condensates





Two trapped condensates

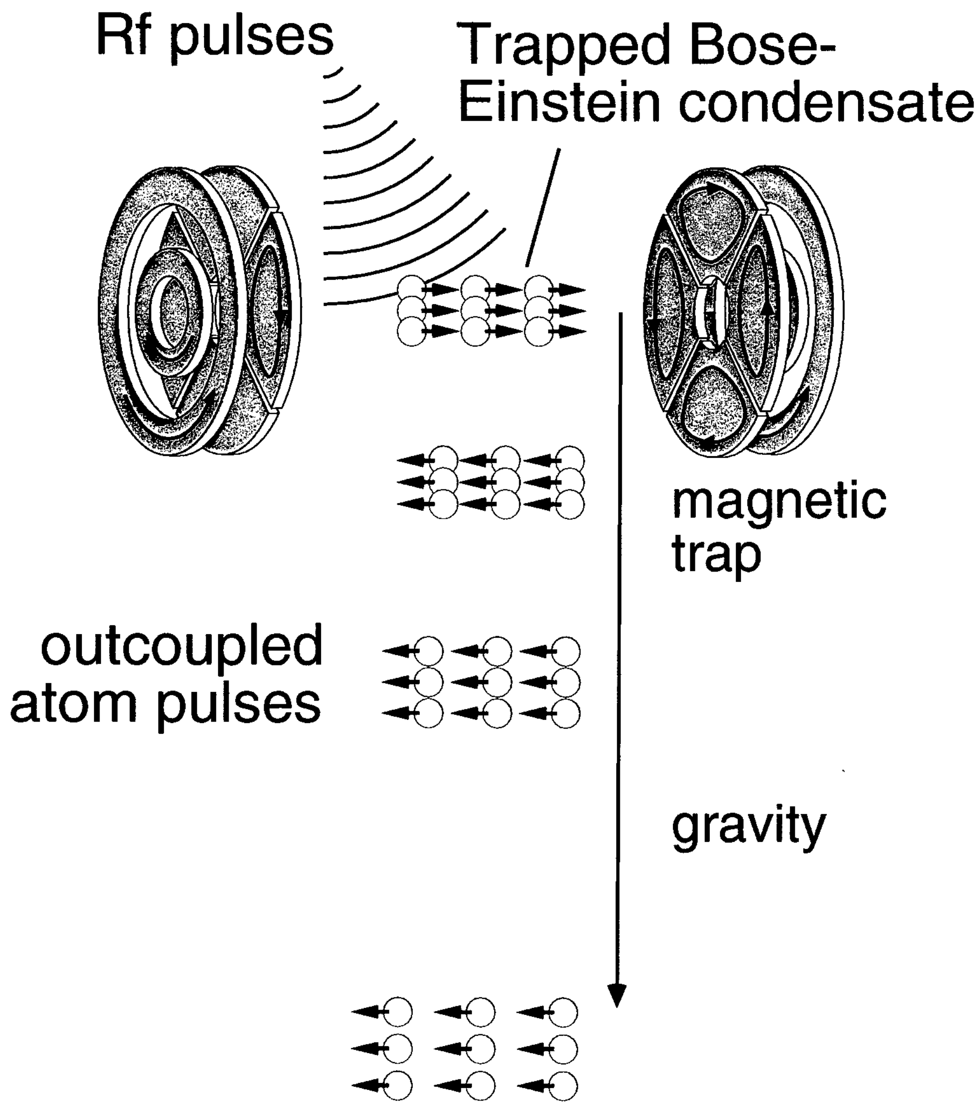
8 mm drop (40 ms) and (anisotropic) expansion

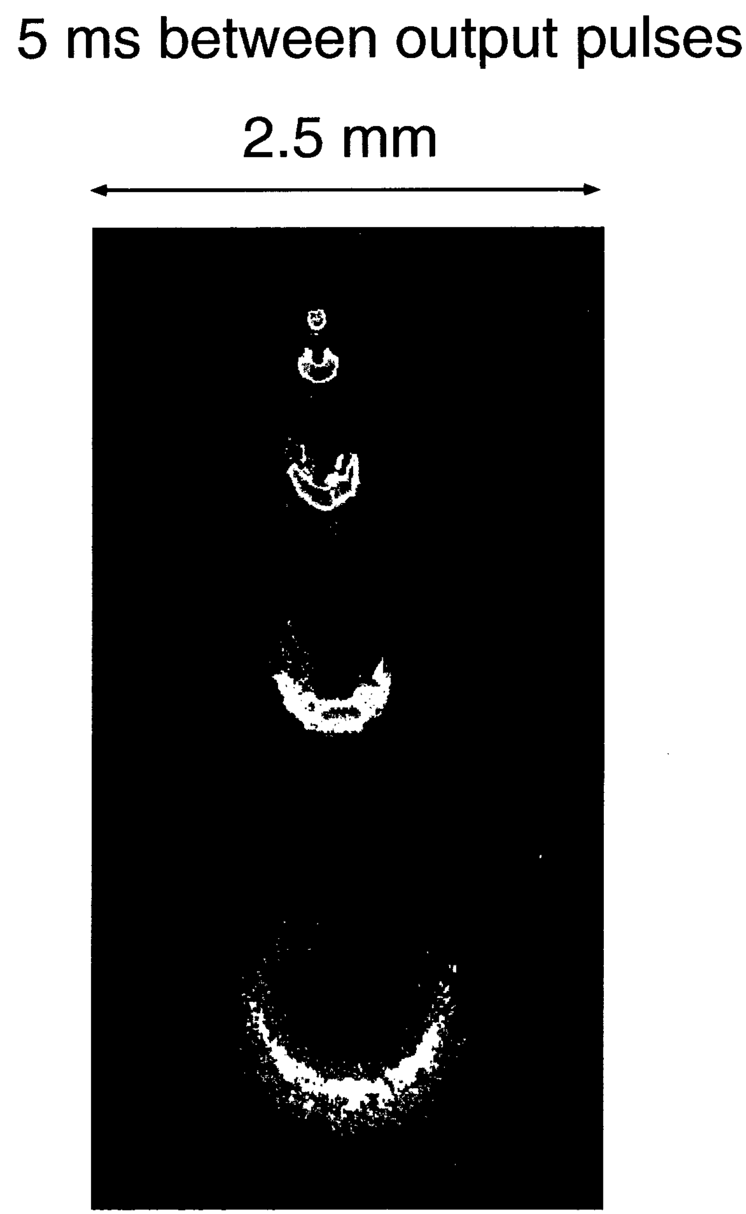


Condensates overlap and interfere

Direct evidence for the coherence of Bose-Einstein condensates

The MIT Atom Laser





GRANT NUMBER: N00014-94-1-0807

FORM A2-2

AUGMENTATION AWARDS FOR SCIENCE & ENGINEERING RESEARCH TRAINING (AASERT) REPORTING FORM

The Department of Defense (DOD) requires certain information to evaluate the effectiveness of the AASERT program. By accepting this Grant Modification, which bestows the AASERT funds, the Grantee agrees to provide the information requested below to the Government's technical point of contact by each annual anniversary of the AASERT award date.

1. Grantee identification data: (R & T and Grant numbers found on Page 1 of Grant)

a. Massachusetts Institute of Technology
University Name

b. N00014-94-1-0807
Grant Number

c. aasert940201
R & T Number

d. Prof. David E. Pritchard
P.I. Name

e. From: 7/1/96 To: 6/30/97
AASERT Reporting Period

NOTE: Grant to which AASERT award is attached is referred to hereafter as "Parent Agreement."

2. Total funding of the Parent Agreement and the number of full-time equivalent graduate students (FTEGS) supported by the Parent Agreement during the 12-month period prior to the AASERT award date.

a. Funding: $ 190,000.

b. Number FTEGS: 2

3. Total funding of the Parent Agreement and the number of FTEGS supported by the Parent Agreement during the current 12-month reporting period.

a. Funding: $ 0

b. Number FTEGS: 0

4. Total AASERT funding and the number of FTEGS and undergraduate students (UGS) supported by AASERT funds during the current 12-month reporting period.

a. Funding: $ 58,918.

b. Number FTEGS: 1.45

c. Number UGS: 0

VERIFICATION STATEMENT: I hereby verify that all students supported by the AASERT award are U.S. citizens.

W. Ketterle
Principal Investigator

6/27/97
Date

GRANT NUMBER: N00014-94-1-0807

ATTACHMENT NUMBER 2

REPORTS AND REPORT DISTRIBUTION

REPORT TYPES

(a) Performance (Technical) Report(s) (Include letter report(s))
FREQUENCY: As required.

(b) Final Technical Report, issued at completion of Grant.

(c) Final Financial Status Report (SF 269)

(d) University Research Initiative (URI)-Augmentation Awards for Science & Engineering Research Training (AASERT) Report (Use attached Form A2-2)

REPORT DISTRIBUTION

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